Fusion-fission dynamics and perspectives of superheavy element formation

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The interest in the synthesis of super-heavy nuclei has lately grown due to the new experimental results [1] demonstrating a real possibility of producing and investigating the nuclei in the region of the so-called “island of stability”. The new reality demands a more substantial theoretical support of these expensive experiments, which will allow a more reasonable choice of fusing nuclei and collision energies as well as a better estimation of the cross sections and unambiguous identification of evaporation residues (ER). The talk will focus on reaction dynamics of superheavy nucleus formation and decay at beam energies near the Coulomb barrier. The aim will be to review the things we have learned from recent experiments [1,2] on fusion-fission reactions leading to the formation of compound nuclei with $Z^{3}102$ and from their extensive theoretical analysis [3-6]. Major attention is paid to the dynamics of formation of very heavy compound nuclei taking place in strong competition with the process of fast fission (quasi-fission). The choice of collective degrees of freedom playing a principal role, finding the multi-dimensional driving potential and the corresponding dynamic equations of motion regulating the whole process are discussed along with a new approach proposed in [3,5] to description of fusion-fission dynamics of heavy nuclear systems based on using the two-center shell model idea. A possibility of deriving the fission barriers of superheavy nuclei directly from performed experiments is of particular interest here. In conclusion the results of detailed theoretical analysis of available experimental data on the "cold" and "hot" fusion-fission reactions will be presented. Perspectives of future experiments will be discussed along with additional theoretical studies in this field needed for deeper understanding of the fusion-fission processes of very heavy nuclear systems.

A whole process of super-heavy nucleus formation can be divided into three reaction stages. At first stage colliding nuclei overcome the Coulomb barrier and approach the point of contact $R_{cont}=R_1+R_2$. Quasi-elastic and deep-inelastic reaction channels dominate at this stage leading to formation of projectile-like and target-like fragments (PLF and TLF) in exit channel. At sub-barrier energies only small part of incoming flux with low partial waves reaches the point of contact. Denote the corresponding probability as $P_{cont}(l,E)$. At the second reaction stage touching nuclei evolve into the configuration of almost spherical compound mono-nucleus. For light or very asymmetric nuclear systems this evolution occurs with a probability close to unity. Two touching heavy nuclei after dynamic deformation and exchange by several nucleons may re-separate into PLF and TLF or may go directly to fission channels without formation of compound nucleus. The later process is usually called quasi-fission. Denote a probability for two touching nuclei to form the compound nucleus as $P_{CN}(l,E)$. At third reaction stage the compound nucleus emits neutrons and γ-rays lowering its excitation energy and forming finally the residual nucleus in its ground state. This process takes place in strong competition with fission (normal fission), and the corresponding survival probability $P_{xn}(l,E^*)$ is usually much less than unity even for low-excited superheavy nucleus.

Thus, the production cross section of a cold residual nucleus B, which is the product of neutron evaporation and γ-emission from an excited compound nucleus C, formed in the fusion process of two heavy nuclei $A_1+A_2\to C\to B+xn+N\gamma$ at center-of mass energy E close to the Coulomb barrier in the entrance channel, can be decomposed over partial waves and written as

$$\sigma^{xn}_{ER}(E) \approx \frac{\pi\hbar^2}{2\mu E}\sum_{l=0}^{\infty}(2l+1)P_{cont}(l,E)P_{CN}(A_1+A_2 \to C;l,E)P_{xn}(C \to B;l,E^*) \quad (1)$$

Different theoretical approaches are used for analyzing all the three reaction stages. However, the dynamics of the intermediate stage of the compound nucleus formation is the most vague. Setting here $P_{xn}=1$ we get the cross section of CN formation σ_{CN}, which can be measured by detection of ERs and fission fragments forming in normal fission (if they are distinguished from quasi-fission fragments and from products of deep inelastic collision). Setting in addition $P_{CN}=1$ we get the capture cross section σ_{cap}, which can be measured by detection of all fission fragments (if they are distinguished from products of deep inelastic collision). For symmetric fusion reactions σ_{CN} and σ_{cap} cannot be measured experimentally.

Coupling with the excitation of nuclear collective states (surface vibrations and/or rotation of deformed nuclei) and with nucleon transfer channels significantly influences the capture cross section at near-barrier energies. Incoming flux has to overcome in fact the multi-dimensional ridge with the height depending on orientation and/or dynamic deformation. In [3,4] a semi-empirical approach was proposed for calculating the penetration probability of such multi-dimensional potential barriers. The capture cross sections calculated within this approach are shown in Fig. 1 for the three reactions (solid curves). They are compared with theoretical calculations made within a model of one-dimensional barrier penetrability for spherical nuclei (dashed curves). In all three cases a substantial increase in the barrier penetrability is observed in the sub-barrier energy region. Good agreement between the calculated and experimental capture cross sections allows us to believe that we may get rather reliable estimation of the capture cross section for a given projectile-target combination if there are no experimental data or these data cannot be obtained at all (symmetric combinations).

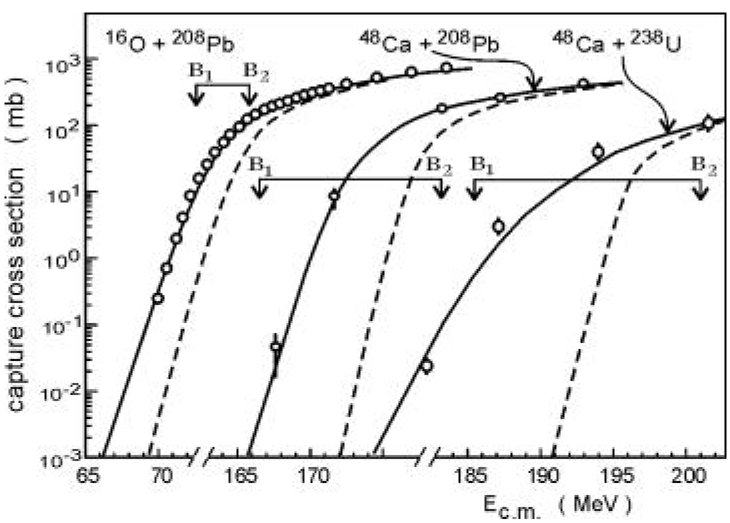

Figure 1. Capture cross sections in the $^{16}O+^{208}Pb$, $^{48}Ca+^{208}Pb$, and $^{48}Ca+^{238}U$ fusion reactions. Dashed curves represent one-dimensional barrier penetration calculations with the Bass barriers. Solid curves show the effect of dynamic deformation of nuclear surfaces (two first reactions) and orientation of statically deformed nuclei ($^{48}Ca+^{238}U$ case).

The processes of the compound nucleus formation and quasi-fission are the least studied stages of heavy ion fusion reaction. To solve the problem we have to answer very principal questions. What are the main degrees of freedom playing most important role at this reaction stage? What is the corresponding driving potential and what are appropriate equations of motion for description of time evolution of nuclear system at this stage? Today there is no consensus for the answers and for the mechanism of the compound nucleus formation itself, and quite different, sometimes opposite in their physics sense, models are used for its description. In [3,5] a new approach was proposed for description of fusion-fission dynamics based on a simplified semi-empirical version of the two-center shell model idea [7]. It is assumed that on a way from the initial configuration of two touching nuclei to the compound nucleus configuration and on reverse way to the fission channels the nuclear system consists of two cores (Z_1,N_1) and (Z_2,N_2) surrounded with a certain number of common (shared) nucleons ΔA=ACN-A1-A2 moving in the whole volume occupied by the two cores. The processes of compound nucleus formation, fission and quasi-fission take place in the space (Z_1,N_1,β_1;Z_2,N_2,β_2), where β_1 and β_2 are the dynamic deformations of the cores. The compound nucleus is finally formed when two fragments A_1 and A_2 go in its volume, i.e., at $R(A_1)+R(A_2)=RCN$ or at $A_1^{1/3}+A_2^{1/3}=ACN^{1/3}$.

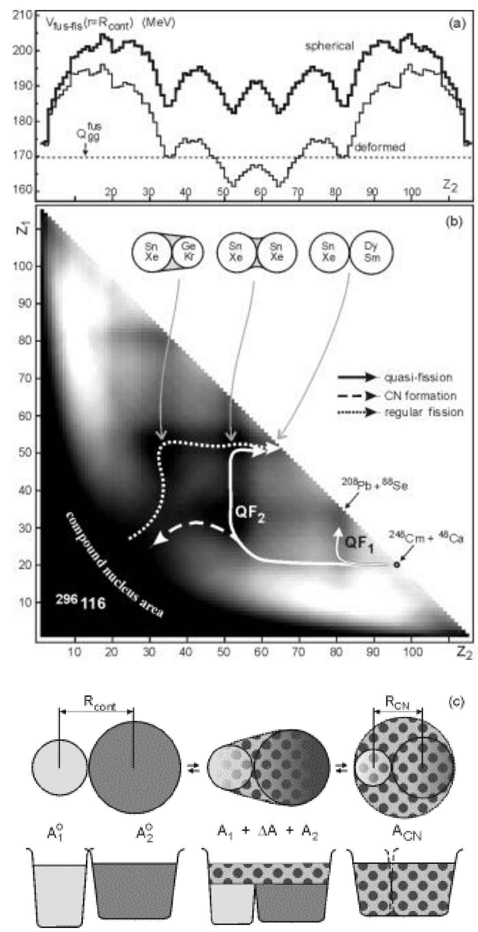

Figure 2. Driving potential $V_{fus\text{-}fis}(Z_1,Z_2)$ of the nuclear system consisting of 116 protons and 180 neutrons. (a) Potential energy of two touching nuclei at $A_1+A_2=A_{CN}$, $\Delta A=0$, i.e., along the diagonal of the lower figure. The thick line corresponds to the case of spherical nuclei, whereas the thin line corresponds to $\beta_1+\beta_2=0.3$. (b) Topographical landscape of the driving potential on the plane (Z_1, Z_2) (zero deformations). The dark regions correspond to the lower potential energies (more compact configurations). (c) Schematic view of the process of compound nucleus formation, fission and quasi-fission in the space of A_1, A_2 and ΔA, i.e., the number of nucleons in the projectile-like nucleus, target-like nucleus, and shared nucleons, here $A_1+A_2+\Delta A=A_{CN}$.

The corresponding driving potential $V_{fus\text{-}fis}(r, Z_1, N_1, \beta_1, Z_2, N_2, \beta_2)$ was derived in [3] and is shown in Fig. 2 as a function of Z_1, Z_2 (minimized over N_1, N_2 and at fixed values of $\beta_1+\beta_2$). There are several advantages of the proposed approach. The driving potential is derived basing on experimental binding energies of two cores, which means that the "true" shell structure is taken into account. The driving potential is defined in the whole region $R_{CN} < r < \infty$, it is a continuous function of r at $r=R_{cont}$, and it gives the realistic Coulomb barrier at $r=R_B>R_{cont}$. At last, instead of using the variables (A_1,A_2), we may easily recalculate the driving potential as a function of mass asymmetry $(A_1-A_2)/(A_1+A_2)$ and elongation $R_{12} = r_0 (A_1^{1/3}+A_2^{1/3})$ (at $r > R_{cont}$, $R_{12} = r = s+R_1+R_2$, where s is the distance between nuclear surfaces). These variables along with deformation $\beta_1+\beta_2$ are commonly used for description of fission process. The corresponding driving potential is shown in Fig. 3.

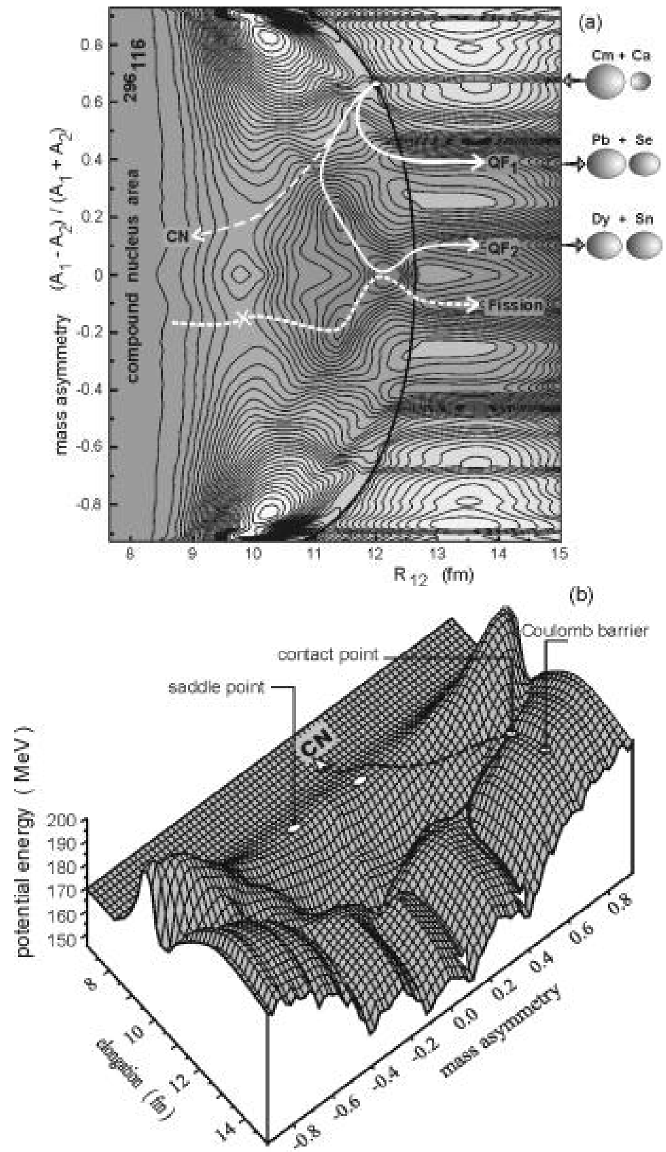

Figure 3. Driving potential $V_{fus\text{-}fis}$ as a function of mass asymmetry and distance between centers of two nuclei with the deformations $\beta_1+\beta_2=0.3$, topographical landscape (a) and three-dimensional plot (b). The black solid curve in (a) shows the contact configurations. The paths QF_1 and QF_2 lead to the asymmetric and near-symmetric quasi-fission channels, the dashed curve shows the most probable way to formation of the compound nucleus, and dotted curve corresponds to the normal (regular) fission. See the conformity with Fig. 2.

As can be seen from Fig. 2 and Fig. 3, the shell structure, clearly revealing itself in the contact of two nuclei (Fig. 2a), is also retained at $\Delta A \neq 0$ ($R_{12}<R_{cont}$), see the deep minima in the regions of $Z_{1,2}$—50 and $Z_{1,2}$—82 in Fig. 2b. Following the fission path (dotted curves in Fig. 2b and Fig. 3) the system overcomes a multi-humped fission barrier, which is well known in fission dynamics. The intermediate minima correspond to the shape isomeric states. From our analysis we may definitely conclude that these isomeric states are nothing else but two-cluster configurations with magic or semi-magic cores (see the inset in Fig. 2b).

As regards the superheavy compound nucleus formation in the fusion reaction ^{48}Ca+^{248}Cm, one can see that after the contact, the nuclear system may easily decay into the quasi-fission channels (mainly asymmetric: Se+Pb, Kr+Hg and also near-symmetric: Sn+Dy, Te+Gd) - solid arrow lines in Fig. 2b and Fig. 3. Only a small part of the incoming flux reaches a compound nucleus configuration (dashed arrow line). The experimental data on the yield of quasi-fission fragments in collisions of heavy nuclei [2] were found quite understandable in terms of multi-dimensional potential energy surface shown in Fig. 2 and Fig. 3 [6].

Using the driving potential $V_{fus\text{-}fis}(Z_1, N_1, \beta_1, Z_2, N_2, \beta_2)$ we may determine the probability of the compound nucleus formation $P_{CN}(A_1+A_2 \rightarrow C)$, being part of expression (1) for the cross section of the synthesis of super-heavy nuclei. It was by solving the transport equation for the distribution function $F(Z_1, N_1, \beta_1, Z_2, N_2, \beta_2;t)$. The probability of the compound nucleus formation is determined as an integral of the distribution function over the region $R_1+R_2 <= R_{CN}$. Similarly one can define the probabilities of finding the system in different channels of quasi-fission, i.e., the charge and mass distribution of fission fragments measured experimentally. Results of such calculations demonstrate quite reasonable agreement with the corresponding experimental data.

The detailed theoretical analysis of available experimental data on the "cold" and "hot" fusion-fission reactions has been performed and the cross sections of superheavy element formation have been calculated up to Z_{CN}=120 as well as the mass and charge distributions of quasi-fission fragments obtained in these reactions. The corresponding excitation functions for 2n, 3n, and 4n evaporation channels were calculated depending on different theoretical estimations of the neutron separation energies and fission barriers of superheavy nuclei. Optimal beam energies were found for production of the cold evaporation residues of new elements in the "hot" fusion reactions. We found also a possibility of deriving the fission barriers of superheavy nuclei directly from analysis of experimental data on the fusion-fission cross sections and from experimental data on the survival probability of those nuclei in evaporation channels of 3 and 4 neutron emission. In particular, the lower limits that we have obtained for the fission barrier heights of $^{283\text{-}286}$112, $^{288\text{-}292}$114 and $^{292\text{-}296}$116 nuclei are 5.5, 6.7 and 6.4 MeV respectively [6], which are really quite high resulting in relatively high stability of these nuclei.

References

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